Limitations of ad hoc "SKA+VLBI" configurations & the need to extend SKA to trans-continental dimensions

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The angular resolution of the proposed Square Kilometre Array, SKA, must be extended towards the milliarcsecond scale if it is to resolve the distant starburst galaxies that are likely to dominate the radio source counts at micro and sub-microJy flux levels. This paper considers the best way of extending SKA's angular resolution towards the milliarcsecond scale. Two possible SKA-VLBI configurations have been investigated and simulated SKA and SKA-VLBI visibility data sets generated. The effects of non-uniform data weighting on the associated images are considered. The results suggest that the preferred option is for SKA to be extended to trans-continental dimensions. By retaining 50% of the array's collecting area within a region no larger than 50 km, the surface brightness sensitivity of the array at arcsec resolution is hardly compromised. In this configuration SKA's capabilities are impressive: in a single 12 hour run, between $100 - 1000$ sources will be simultaneously detected and imaged with arcsecond, sub-arcsecond and milliarcsecond resolution.

1 Introduction

The technique of Very Long Baseline Interferometry (VLBI) permits astronomers to generate milli and sub-milliarcsecond resolution images of galactic and extra-galactic radio sources. VLBI has evolved rapidly in the last decade with significant improvements in resolution, polarisation imaging and spectral-line capabilities. In terms of raw sensitivity, however, the gains have been more modest, especially at cm-wavelengths. Although the technique of phase-referencing has recently permitted the detection and (limited) imaging of sources at the mJy flux level, the current state-of-the-art r.m.s. image noise level is still limited to $\sim 30\mu$Jy/beam at cm-wavelengths (for a typical on-source observing run of 12 hours). The recent introduction of the 1 Gbit/sec MkIV system and other technical improvements promise to improve this by a factor of 3 or so, thus reducing the r.m.s. image noise level to $\sim 10\mu$Jy/beam.

While this is all very encouraging, a more sobering thought is that even at these r.m.s. noise levels, the overlap between the radio sky and the sky at optical and infra-red wavebands is rather limited. It is only by going deeper – much deeper – that the optical and radio source counts become comparable. If complimentary observations are to be achieved, and radio astronomy is to remain at the very forefront of astrophysical research, it is imperative that noise levels are reduced by at least two orders of magnitude.

The Square Kilometer Array, SKA, currently offers the best possibility of achieving these kind of noise levels. However, sensitivity is not the only issue, one must also consider what angular resolution is required - not simply to avoid the limitations imposed by source confusion but to properly investigate the radio morphology of the sources that will dominate the μJy and sub-μJy radio source population.

The tendency for faint sources to be considerably smaller than their brighter counterparts has been known for some time (Oort 1987 [1] and Fletcher et al. 1998 [2]), and is strikingly confirmed by the relatively high detection rates of recent VLBI surveys of faint mJy radio sources (Garrington, Garrett & Polatidis 1999 [3]). For compact AGN this phenomenon can be easily understood in terms of synchrotron self-absorption theory: for a given magnetic field strength, smaller sources will also be fainter sources. High resolution imaging is therefore of considerable importance to the study of faint AGN.

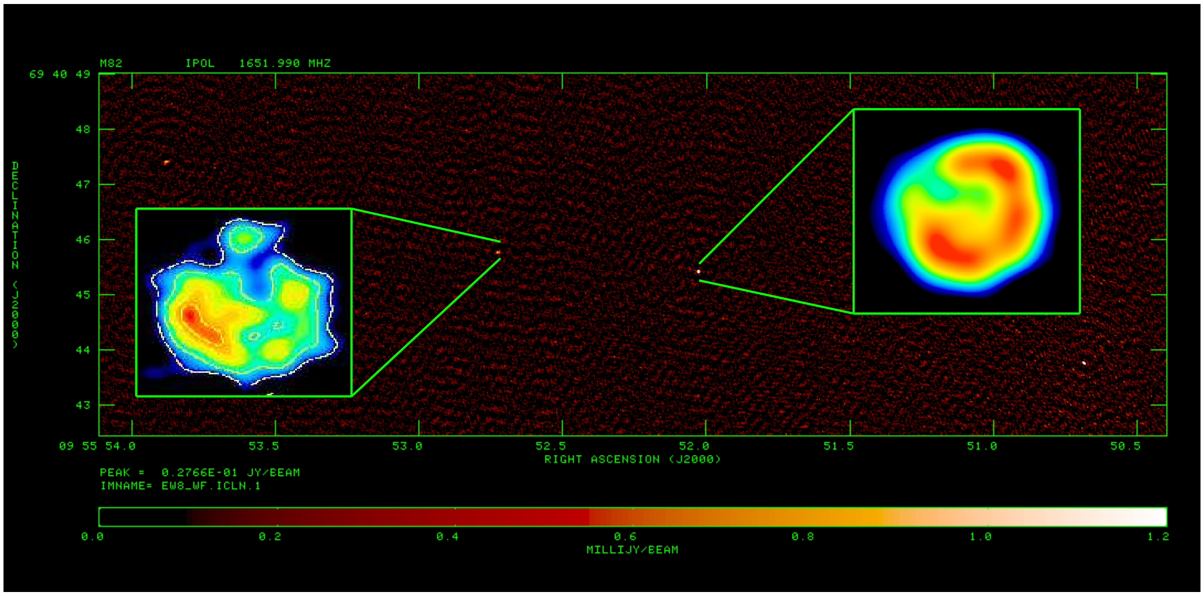

Figure 1: Wide-field EVN λ18 cm observations of M82 (Pedlar et al. 1999) reveal SNR shells ranging in diameter from 0.6 to 1.4 pc. Evidence for clear expansion in the remnant highlighted in the upper right-hand corner of this figure, is consistent with a SN event in the early 1960's. The image is a good example of the current VLBI state-of-the-art: the entire 1 arcminute field was imaged in wide-field, phase-reference mode. The faintest remnant has a total flux density of 2.6 mJy and the r.m.s. noise in the image is $\sim 50\mu$Jy/beam.

Perhaps a more significant factor in this discussion, however, is the emergence of a new population of radio sources as suggested by the flattening radio source counts at sub-mJy flux density levels, now confirmed with the recent radio studies of the Hubble Deep Field (Richards et al. 1998 [4] and Muxlow et al. 1999 [5]). These pioneering observations strongly suggest that the bulk of the μJy radio source population is dominated by distant starburst galaxies, rather than AGN.

The nearest and best studied starburst galaxy is undoubtedly M82. Located only ~ 3 Mpc away, its radio emission is concentrated within the central few kpc of the galaxy [6] and is dominated by radio emission from both recent and relic supernova remnants (SNRs). Fig. 1 shows a superb, wide-field EVN λ18 cm image of M82 produced by Pedlar et al. (1999) [7].

If M82 is typical of higher redshift starbursts (and recent VLBI observations by Smith et al. 1999 [8] of the more vigorous and distant starburst, Arp 220, suggest that it may well be), we can expect to detect with SKA individual SNR in starburst galaxies out to cosmological distances - at least in terms of sensitivity. But this is only part of the story. If the SNR are distributed on scales similar to that observed in both Arp 220 and M82, then at $z = 1.5$ the bulk of the radio emission will occupy a region of sky no greater than 60 milliarcseconds across. Thus in order to properly resolve these systems into their constituent parts, resolutions of a few mas are required.

While this is not the only argument for high resolution SKA observations (see contributions by Gurvits, Krichbaum, Snellen, Phinney, Roy, Koopmans & Fender - these proceedings) it is a very powerful one: the idea that SKA will only barely resolve the dominant sources of radio emission in the sky (Wilkinson's "bread and butter sources" - these proceedings) is surely unthinkable, at least for a true "next-generation" instrument.

In this paper, I discuss the ways in which the angular resolution of SKA can be extended towards the milliarcsecond scale. I do not make the conventional assumption that SKA's only contribution to the field of VLBI is as an ultra-sensitive, phased-array "add-on" to existing VLBI networks. Although this scenario is considered other options are investigated and indeed preferred, including the extension of SKA to trans-continental dimensions.

I first consider in section 2 a few minor technicalities regarding SKA and VLBI baseline sensitivity (in particular the possibility of employing in-beam phase referencing techniques), and the need for a wide-field approach to VLBI observations at these sub-μJy levels. In Section 3 I present the first realistic simulations of various SKA-VLBI configurations including an extended version of SKA (designated "SKA^{++}"), in which half of the SKA antennas are located within an array of 50 km and the other half are separated by trans-continental distances. A discussion of the main results and conclusions are presented in sections 4 and 5 respectively.

2 SKA-VLBI: minor technicalities

Throughout this paper I adopt the nominal SKA parameters of Taylor & Braun (1999) [9] *i.e.* thirty, 200-m diameter elements with a total observing bandwidth of 1500 MHz at λ6 cm, 2-bit sampled data and a total sensitivity figure of $2 \times 10^4 \mathrm{m}^2/\mathrm{K}$. In this section we discuss some minor technicalities that have not been previously considered in earlier SKA-VLBI discussions.

2.1 SKA & VLBI baseline sensitivity

The 7σ baseline detection level between a phased-array SKA, (*i.e.* $\mathrm{SKA_{PA}}$ with 80% of the total collecting area formed by those antenna elements lying within 50 km of each other, SEFD ~ 0.17 Jy) and a single 25-m VLBA antenna (SEFD $\sim$ 290Jy) is $\sim 60\mu$Jy, assuming a coherent integration time of 300 seconds at λ6 cm. At these levels of sensitivity the radio source counts are fairly well understood: the recent VLA HDF observations of Richards et al. (1998) [4], together with earlier VLA observations including those of Windhorst et al. (1995) [10], suggest the source count is of order $20\mathrm{S}(\mu\mathrm{Jy})^{-1}$ arcmin^{-2}. Thus within the FWHM of a 25-m antenna's primary beam, we can expect to find at least 15 sources above the 10σ noise level, of which 5 can reasonably be expected to be stronger than the 30σ noise level. Naturally these latter sources can be used as "in-beam" (phase) calibrators, able to provide continuous and accurate instrumental corrections without the need for conventional phase-referencing (note that in this scenario the multiple beam capability of SKA in its phased-up mode is assumed since the field of view of the phased-array is otherwise rather limited). At λ18cm the situation is even better with at least 45 potential calibrator sources in the primary beam of a 25-m antenna. In short, in-beam calibration will be possible in the vast majority of cases at cm wavelengths.

2.2 Imaging large fields-of-view

At the SKA detection level of 100 nanoJy we can (with a little extrapolation!) predict a source count of at least ~ 100 sources/arcmin^2. Clearly the sky will be densely populated with radio sources separated by only a few arcseconds, perhaps less, if clustering is important (as one might expect). Independent of whether we consider SKA as a standalone array (with baseline lengths of at least 1000 km) or as part of a VLBI network, we can expect to image hundreds of sources simultaneously from just a single area of sky covered by one (single element) SKA beam. Already the application of wide-field imaging techniques is beginning to find a place in VLBI (Garrett et al. 1999 [11]) but in the era of SKA, a wide-field imaging mode will be the *de facto* mode of operation - even at milliarcsecond resolutions. This will require *at least* the full spectral resolution of SKA at the longest wavelengths (10^4 spectral channels) and sub-second integration times at the shortest cm wavelengths in order to avoid smearing. A typical 12 hour run by the SKA-VLBI configurations discussed further in this paper, will result in a substantial but hopefully not unmanageable data size of ~ 1 Tera Byte.

3 SKA & VLBI: issues of sensitivity and weight

Various authors have previously considered the sensitivity gain one achieves by including SKA as part of a large VLBI network or extending it to trans-continental baselines (*e.g.* Schilizzi & Gurvits, section 2.5.2 in Taylor and Braun [9]). In this section we extend these calculations by taking into account the effect of data weighting and the necessary trade-off between sensitivity and resolution for some proposed SKA-VLBI configurations.

3.1 Weighty matters

At face value the inclusion of SKA as part of a large VLBI network results in an array with superb uv-coverage, high resolution and sub-μJy sensitivity. However, predictions of image noise levels (and uv-coverage) which do not take into account the relative weights of the contributing baselines, can be misleading. For example, if we consider an array formed by the individual SKA elements (SKA_1), in the nominal configuration of Taylor & Braun, observing together with a global VLBI array (GVLBI), then for naturally weighted data the array is entirely dominated by the very sensitive baselines formed between SKA elements. Since the vast majority of these present baseline lengths of order 50 km or less, the dirty beam associated with such naturally weighted data does not even begin to provide the sort of milliarcsecond (mas) resolution expected from a VLBI array of global dimensions. Alternatively if SKA is included as a phased-array, SKA_{PA}, the situation is even more extreme in terms of the effective uv-coverage since only the SKA_{PA} baselines actually contribute to the synthesised image. In either case, the only way to achieve uniform uv-coverage is to abandon natural weighting and re-weight (*i.e.* weight-up) the noisier baselines, thus increasing the image noise level by factors of several - well beyond the original expectation.

3.2 SKA-VLBI data simulations

In order to investigate these effects semi-quantitatively, I have generated three simulated SKA (and VLBI) visibility data sets. In order to serve as a reference point, simulated data were first generated for the nominal SKA configuration of Taylor & Braun (1999) [9]. Two additional options were considered with respect to how SKA provides high sensitivity observations with milliarcsecond scale resolution: (i) SKA contributes as a sensitive, phased-array "add-on" to the existing global VLBI network ("SKA_{PA}-GVLBI"), and (ii) SKA is extended to trans-continental baselines, SKA^{++} but 1/2 of the antennas still remain within 50 km of each other in order to maintain good brightness sensitivity at arcsecond resolution.

3.2.1 Source Model

The source model used to produce the simulated λ6 cm data is shown in Fig. 2. It represents a "best guess" of what the μJy source population might look like – essentially it is based on an M82/Arp 220-type starburst, projected back to a redshift of $z \sim 1.5 - 2$. The radio emission is concentrated within the inner few kpc (120 mas) of the galaxy, and dominated by young SNRs, relic SNRs and compact HII regions. In addition, I have added a low-luminosity AGN slightly offset from the plane of star formation which accounts for $\sim 20\%$ of the total flux density of 14 μJy. Although an AGN has not yet been identified in either Arp 220 or M82, it might not be too surprising to find such low-luminosity AGN in some starburst galaxies. The faint radio sources identified with starburst galaxies in the HDF, appear to have very distorted morphologies, suggesting they were recently involved in interactions with their nearest companions or complete mergers. While this is certainly a trigger for rapid bursts of star formation, it may also initiate AGN activity (or re-initiate it) in the centres of these galaxies.

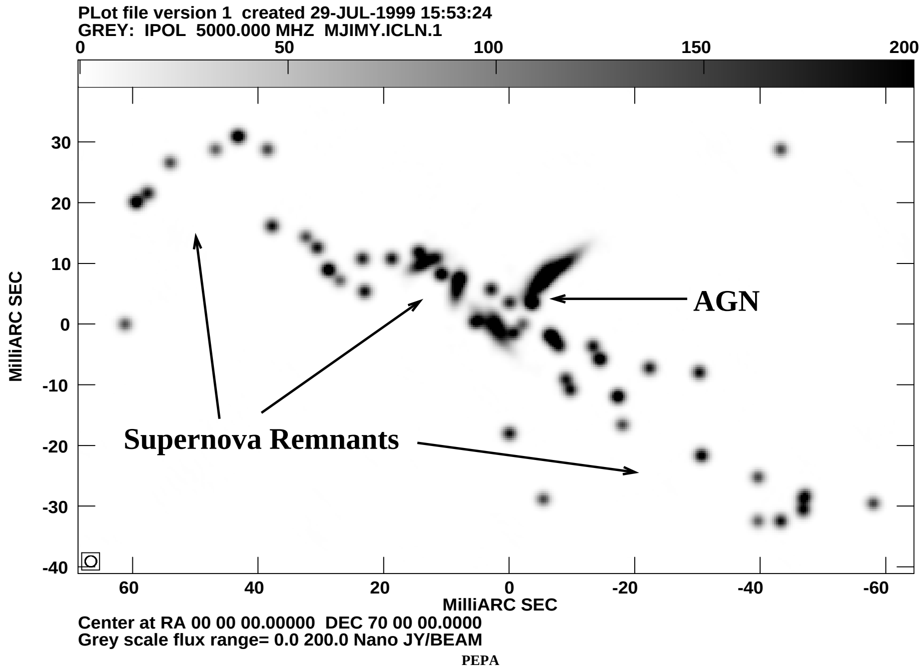

Figure 2: The model source convolved with a 1.8 mas circular beam. The source spans a region 120 milliarcseconds across. The total flux is 14μJy.

3.2.2 Data Generation

The AIPS task UVCON was used to generate the λ6 cm simulated data sets. The nominal SKA configuration (Taylor & Braun 1999 [9]) was initialy assumed, with the array arbitrarily centred on Dwingeloo, the Netherlands. Data were generated between hour angles of $\pm$6 hours (as calculated at the centre of the array). UVCON adds Gaussian noise to each visibility based on the specified antenna characteristics (diameters, efficiency, noise temperature, data sampling/rate etc). For the elements of SKA the following parameters were chosen: 30 identical elements of 200 m diameter and 60 K system temperatures with a combined sensitivity figure of $\sim 2 \times 10^4 \mathrm{m}^2/\mathrm{K}$.

3.2.3 Simulated SKA Images

Fig. 3 shows a simulated λ6 cm image of the model source generated by the nominal SKA configuration. The data were Fourier transformed and CLEANed using the AIPS task IMAGR. The image was produced with (Robust=-2) uniform weighting (see Briggs 1995 [12] for a discussion of Robust weighting). This weights the data at a level which is intermediate between natural weighting (the case in which visibility weights are simply proportion to the inverse of the r.m.s. noise squared) and pure uniform weighting (all data points have equal weights irrespective of their variance and the local data density in the uv-plane). This weighting is necessary in order for the nominal SKA configuration to provide the 10 mas resolution one expects for an array in which the longest baselines are $\sim$ 1000 km. The naturally weighted image provides only 20 mas resolution since the uv-plane is so densely populated by the inner 50 km region of the array where 80% of the collecting area resides. However, even the 10 mas resolution obtained from the uniformly weighted data is not sufficient to do much better than partially resolve the radio source. The noise in this image is $\sim 0.05\mu$Jy/beam, almost twice as high as the noise in the naturally weighted image.

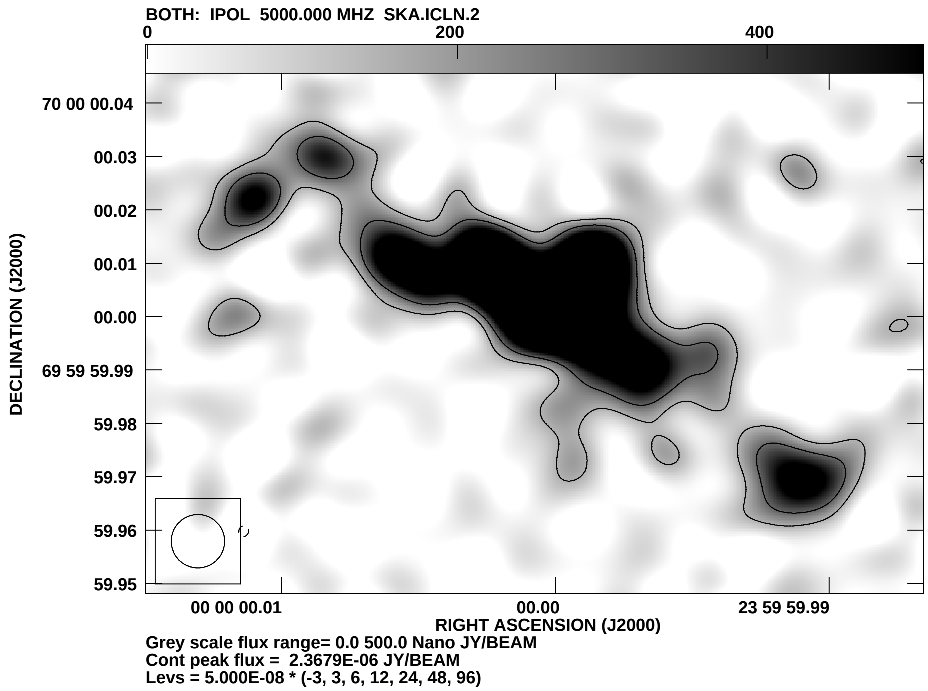

Figure 3: A uniformly weighted $\lambda 6$ cm image produced by the nominal SKA configuration of the starburst model source. The resolution is ~ 10 mas but does not adequately resolve the source. The r.m.s. noise level is $\sim 0.05\mu$Jy/beam.

3.2.4 Simulated "$\mathrm{SKA_{PA}}$+GVLBI" Images

Fig. 4 shows a simulated $\lambda 6$ cm image of the model source generated by a global VLBI network supplemented by the inner 80% of the nominal SKA configuration, phased-up to form a single, highly sensitive VLBI antenna, "$\mathrm{SKA_{PA}}$". This is the traditional SKA-VLBI configuration that is often assumed to be SKA's default contribution to VLBI. The global VLBI network used in these simulations includes 17 of the largest antennas in the world, including the Effelsberg 100-m, $\mathrm{VLA_{27}}$, Greenbank 100-m, DSN 70-m and the new 70-m and 45-m antennas currently under construction in Sardinia (IRA) and Yebes (OAN). As for the previous SKA simulation, we assume the VLBI antennas can also deliver or record data at 6 Gbits/sec (a 2-bit/4-level sampled, single polarisation, 1500 MHz wide IF band). The naturally weighted image has an r.m.s. noise level of 0.17μJy/beam and provides a resolution of 1 mas. The core of the AGN is barely detected but the other sources fall well below the noise level. The image (and the effective uv-coverage) are completely dominated by $\mathrm{SKA_{PA}}$ baselines, the other inter-VLBI antenna baselines have no effect on the image whatsoever. Although this latter effect is yet to be investigated in any detail, the ability of this array to image even moderately extended structures is likely to be limited. Brute force modification of the antenna weights would be required in order to improve the effective coverage but the corresponding impact on sensitivity would be severe.

3.2.5 Simulated "$\mathrm{SKA^{++}}$" Images

Fig. 5 shows a simulated $\lambda 6$ cm image of the model source generated by an extended SKA configuration, "$\mathrm{SKA^{++}}$". In this scenario half of the SKA antennas remain within the inner 50 km of the array but the other half are distributed around the world (in this case the precise locations are a subset of the current EVN and VLBA antenna sites). Note that the inner elements of SKA contribute to the observations as *individual* antennas, not as a phased array

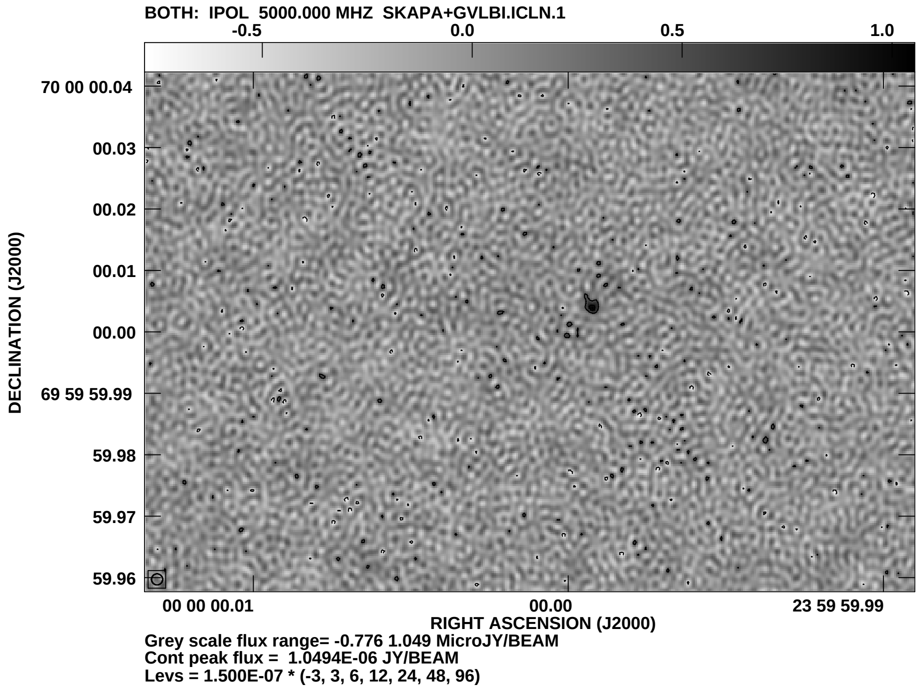

Figure 4: The $\mathrm{SKA_{PA}}$+GVLBI uniformly weighted λ6 cm image of the Starburst model radio source described in the text. The resolution is $\sim$ 1 mas but the combined array is only able to detect the core of the AGN. The fainter SNRs and the extended AGN jet go undetected. The r.m.s. noise level is $\sim 0.17\mu$Jy/beam.

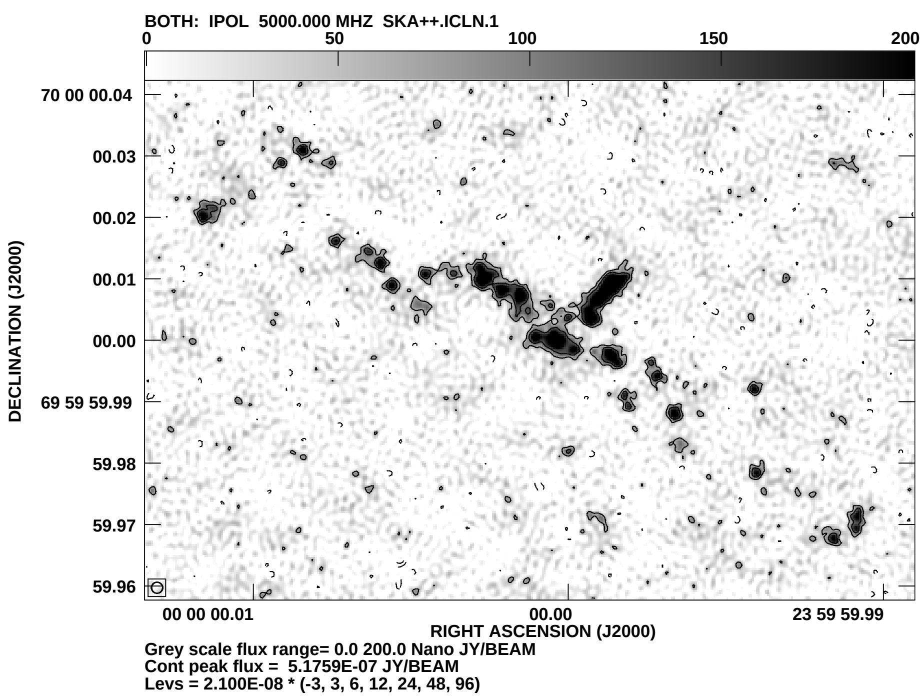

Figure 5: The $\mathrm{SKA^{++}}$ uniformly weighted λ6 cm image of the Starburst model radio source described in the text. The resolution is $\sim$ 1.8 mas permitting the structure source to be revealed in some detail. The r.m.s. noise level is $\sim 0.02\mu$Jy/beam.

(though note that in order to provide the in-beam calibration described in section 2.1, an additional phased array beam may also be required). A "robust=0" uniformly weighted image has an r.m.s. noise level of $\sim 0.02\mu$Jy/beam and provides a resolution of 1.8 mas. The combination of high sensitivity and resolution allows us to resolve the individual SNR from each other and the AGN (which also shows a two-sided jet). The vast majority of the individual SNR themselves remain unresolved; space VLBI resolutions such as those achievable by the proposed ARISE mission (Ulvestad & Linfield 1998 [13]) might be able to detect and thus resolve the brighter remnants (the sensitivity of a combined SKA+ARISE configuration requires its own detailed study, see Gurvits these proceedings).

4 Discussion

The SKA can make a useful contribution to high resolution radio astronomy. However, the nominal SKA configuration with baseline lengths < 1000 km may not provide enough resolution to adequately resolve the structure of the vast majority of the faint, extragalactic radio sources it detects. In my opinion this is a major flaw in the proposed configuration. Higher resolution can be achieved in at least two ways, the conventional option is for SKA to participate within a VLBI network as a highly sensitive phased-array add-on. The second less conventional, but in my opinion preferred option, is for SKA to be extended to trans-continental baselines, SKA^{++}.

The conventional option will allow images to be made with noise levels of $\sim 0.17\mu$Jy/beam, a factor of 60 better than what can be achieved by VLBI today, even in the era of 1 Gbit/sec MkIV recording. The uv-coverage will, however, remain limited, and there is a danger that the coordination and flexibility of the network will be plagued by the problems that beset existing, non-homogeneous, ad hoc arrays.

The SKA^{++} option will allow images to be made with noise levels around 0.02μJy/beam, a factor of 500 better than what can be achieved today and almost an order of magnitude better than the conventional phased-array option. In the SKA^{++} configuration described here, half the antennas are still located within the inner 50 km region of the array, thus satisfying other SKA programmes which require high surface brightness sensitivity at arcsecond resolution. This homogeneous array offers superb uv-coverage, flexibility in operation and all the other benefits associated with SKA, in particular, multiple beams for phase-referencing (although at wavelengths ≥ 6 cm this may not be required since there will almost always be enough "in-beam" calibrators). The possibilities arising from a SKA^{++} instrument are quite simply staggering: with a 1 arcmin field of view, SKA^{++} in a single 12 hour run, could easily detect and image over $\sim 100 - 1000$ sources simultaneously with arcsecond, sub-arcsecond and milliarcsecond resolution.

The feasibility of connecting together SKA elements in real-time over large distances appears feasible, even by today's standards. Considerable activity in the connection of telescopes by optical fibres is on-going around the world with the recent link between the VLBA antenna at Pie Town and the VLA (a distance of ~ 100 km), being the most recent success story. The main difficulties are now considered to be economic rather than technical (Whitney et al. 1999 [14]). With the reasonable expectation that trans-continental fibre connections will fall in price over the next 2 decades, SKA^{++} is a realistic proposal which requires serious consideration and more detailed investigation.

5 Summary: the need for a higher resolution SKA

The quest for higher angular resolution has been one of the key driving forces in observational astronomy, together with improved sensitivity and new spectral bands. Despite the fact that optical telescopes have always enjoyed a natural advantage in terms of source number counts, the ability of radio interferometers such as the VLA, MERLIN and VLBI to generate

sub-arcsecond and milliarcsecond resolution images has allowed them to stay at the very forefront of astrophysics. Comparable radio instruments, in terms of sensitivity but with inferior resolution, have been significantly disadvantaged.

Optical astronomers are now designing the next generation of ground and space based telescopes (*e.g.* the VLTI & NGST). These will have comparable or *better* resolution than that currently proposed for SKA. Similarly, it is now clear that optical and infra-red interferometry will take a giant leap forward in terms of sensitivity and resolution, in the form of the armada of space-based interferometry missions (*e.g.* Gaia, Darwin, SIM etc) currently proposed. On the same time scales envisaged for the completion of SKA, these next generation instruments will provide optical and infra-red astronomers with the ability to perform micro-arcsecond astrometry (allowing the direct detection of nearby extra-solar planets) and sub-milliarsecond resolution imaging of a wide variety of celestial objects. The importance of complimentary, high resolution radio observations will become clear as the surfaces of nearby stars, the ejecta of novae and supernovae, accretion disks and jets around young stars and x-ray binary systems, not to mention the environment around the central engines of extra-galactic objects (normal galaxies and AGN) become the favoured targets of these space-based instruments.

The next generation of radio telescope will surely provide astronomers with unprecedented sensitivity - that much is clear. However, the majority of radio sources it detects will most likely require milliarcsecond resolution to be adequately resolved. Simply relying on occasional, ad hoc "SKA+VLBI" observations to provide this resolution is not, in my opinion, a satisfactory solution. A self-contained SKA can provide milliarcsecond resolution by extending the array to trans-continental dimensions. By retaining 50% of the array's collecting area within a region no larger than 50 km, the surface brightness sensitivity of the array at arcsec resolution is hardly compromised. In this way SKA can be a truly global, next generation radio telescope with unrivaled capabilities over a wide range of angular resolution and surface brightness sensitivity.

Acknowledgments

I'd like to thank Richard Schilizzi for reading the text of this paper critically, and for suggesting several useful improvements that were incorporated into the final version.

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